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PERFORMANCE OF COMMON-MODE CHOKES

BY ANNETTE MUETZE & BEE SEE HENG

IN THIS ARTICLE, A LOW-COST METHod for the experimental investigation of common-mode (CM) chokes for reducing high-frequency (HF) motor-ground currents of inverter-based drive systems of several hundred kilowatts is presented. This method provides a powerful tool during the design stage of such chokes to verify their predicted performance. The HF ground current that can occur in inverter-based drive systems can cause different parasitic phenomena. Depending on the overall system, notably, the drive size and presence of additional mitigation techniques, these parasitic phenomena can lead to early drive failure due to HF-circulating bearing currents and bearing currents due to rotor ground currents [1]–[7]. These effects are increasingly important with increasing machine size. Other phenomena include wide-band electromagnetic interference (EMI) and

Evaluation of a low-cost, low-power test bed

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interference with ground-fault protection systems in industrial facilities [8]–[11]. The CM chokes that are placed in the inverter output (Figure 1) can be a cost-effective method of reducing such ground currents, and reductions of the original HF CM current to as low as 10% have been reported [4], [6], [12]–[14].

As far as the authors know, most of the literature on CM chokes have focused on wound chokes and their application in systems with rather small currents of several amperes only. In such applications, experimental tests can be relatively easy and performed at low cost, when compared with experimental tests with large drives and with motors above 100-kW rated power. Furthermore, the literature on CM chokes generally focuses on their use within passive or active filters and transformers that also eliminate the CM voltage [6], [13], [15]–[18]. Some accounts give special attention to topics related to the design of systems using CM chokes, such as the reduction of the occupied volume [19], [20] or the leakage capacitance of the choke [21] that reduces its effectiveness.

THE HF GROUND CURRENT THAT OCCURS IN INVERTER-BASED DRIVE SYSTEMS CAN CAUSE DIFFERENT PARASITIC PHENOMENA.

Here, in contrast to most of the existing literature, we focus on the use of CM chokes with medium and high-power applications with large motors above 100-kW rated power. As a matter of fact, because of the large magnitude of both the HF ground current and the phase currents, where the latter leads to comparatively bulky motor leads with large diameters, the requirements for such chokes differ from standard choke designs. Notably, use of several single-turn feedthrough chokes in series is likely to be the more practical choice than wound chokes [22], [23] (Figure 2).

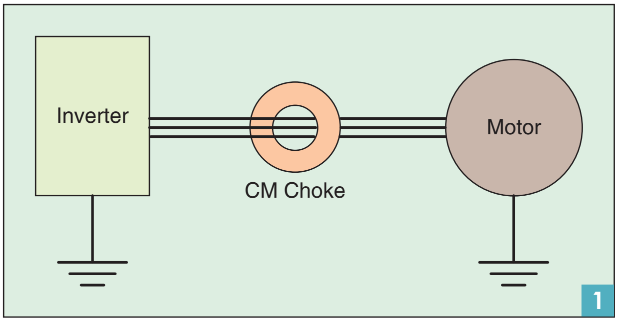
In this article, we report on a low-cost technique to evaluate such CM chokes for higher-power applications on low-cost, low-power, test beds. The method extends an approach that was applied in the context of a series of test runs for bearing damage assessment [24]. More complicated structures such as filters that provide a connection to the inverter-dc link are beyond the scope of this contribution. Modeling techniques for such CM chokes have been developed. These have different degrees of complexity and accuracy, and prediction of the current reduction with high accuracy has been shown to be possible (error $<10\%$ [25]). Depending on the degree of accuracy aimed for, the models can be time consuming to implement and, additionally, may rely on the exact knowledge of the magnetic properties of the material as a function of frequency and magnetic utilization, which are often not easily available. Although modeling techniques can be an important tool to avoid time-consuming and costly trial-and-error evaluation through experimental tests, they should not obscure the necessity of experimental tests at a later stage of the design process. In this context and considering the size of the components normally involved with medium- and high-power drives above 100-kW rated power, a low-cost technique to experimentally evaluate the performance of CM chokes for such applications can be seen as a valuable tool for use during the design stage. This article focuses on the realization of such a method and on a rather straightforward, simple analysis supporting the development of similar test beds. The reported quantitative results

LIST OF ABBREVIATIONS

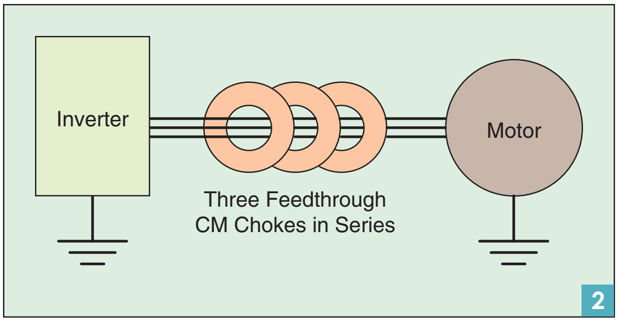
Acronym	Definition
ac	Alternating current
CM	Common mode
EMI	Electromagnetic interference
HF	High frequency

LIST OF SYMBOLS

C	Capacitance
C_a	Capacitance of the additional capacitor(s)
C_m	Capacitance between motor winding and ground
dv/dt	Voltage rise
I_p	Peak current amplitude
$I_{p,0}$	Peak current amplitude without chokes
$I_{XnF,MY}$	Current with C_a = XnF and choke(s) MY
R	Resistance
L	Inductance
L_{self}	Self-inductance of the (short) motor leads
$V_{XnF,MY}$	Voltage with C_a = XnF and choke(s) MY



A simplified sketch to illustrate placement of a CM choke in the inverter output.



A simplified sketch to illustrate the use of several single-turn feedthrough CM chokes in series instead of wound chokes.

shall provide orders of magnitudes that can serve as reference values for the development of further test beds of this kind in other contexts. The abbreviations and symbols used are summarized in the sidebar.

Background and Context

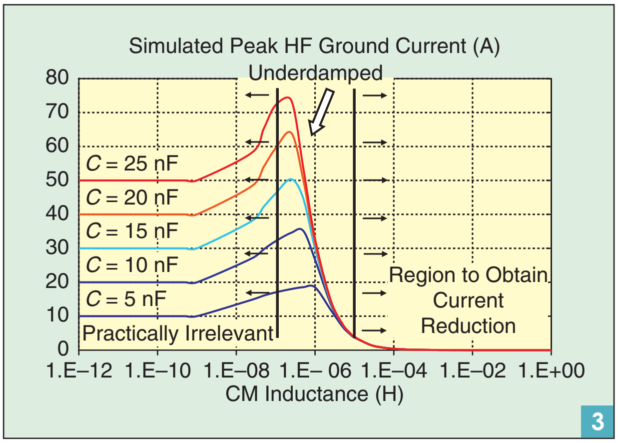
For the analysis and development of the test setup, the machine-inverter configuration is modeled by a per-phase linear network consisting of a resistor R, an inductor L, and a capacitance C (linear RLC network), similar to what is done in [4] and [5]. Each switching transition is analyzed independently, what is justified as the ring period is long compared with the transition time, particularly with large drives and with effectively used CM chokes [23]. The analysis also depends on the resistance value and the degree of damping. As the inductance is increased, the damping is decreased, assuming that the losses in the inductor itself are small. Thus, we are typically interested in low-damping cases. Exemplarily, Figure 3 shows the dependency of the peak current on the inductance value for different capacitance values, $dv/dt = 2\,\mathrm{kV}/\mu\mathrm{s}$, and $R = 1\,\Omega$ (simulation results). With $C \approx 10$ nF and $C \approx 24$ nF for machines with 315- and 400-mm shaft height, respectively, the HF ground current of the fan-cooled machine is 15–25% of the rated current when no mitigation technique is applied, corresponding to the simulated values, and what has also been observed experimentally [7].

With respect to the choke design, use of the simplified RLC circuit is limited. As outlined in the introduction, saturation, nonlinearity, and parameter dependency on frequency and magnetic utilization are not considered. However, for the development of the test setup, this circuit is appropriate, since we aim to generate the HF ground-current amplitudes so as to verify the performance of the previously selected and/or designed CM chokes, where the limitations of the RLC circuit influence the latter, the choke selection/design, but not as much the development of the test setup.

Test Setup

Base Configuration, Without CM Chokes

The base configuration consists of a 4-kW 230-V insulated-gate bipolar transistor (IGBT) inverter, a 11-kW squirrel-cage induction motor, and one very short no. 6 stranded wire motor-inverter interconnect of only 25 cm length. Only one motor terminal and one inverter leg are connected. The cable is kept at a minimum length to limit its influence on the ground-current generation. Without any additional devices, the measured peak HF ground current is $I_p = 11.9$ A, which is a typical value for a drive of this rating. This amplitude is increased artificially by more than 500% as follows: drawing

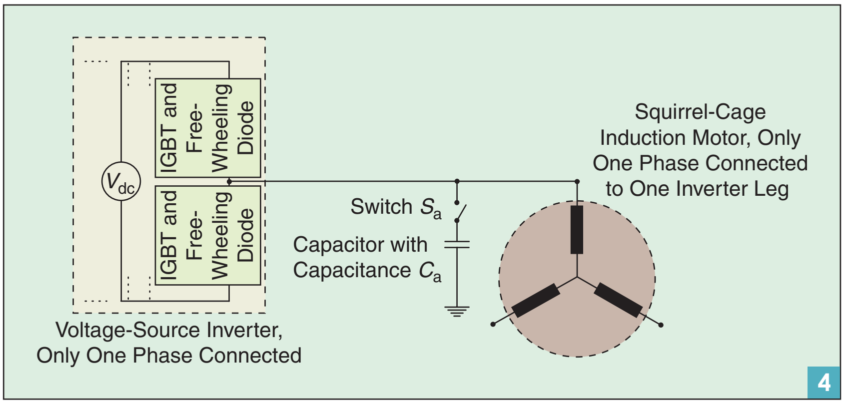


Dependency of peak current on inductance values, for different capacitance values $dv/dt = 2\,\mathrm{kV}/\mu\mathrm{s}$ at $R = 1\,\Omega$.

from the understanding that off-the-shelf machines show mainly capacitive behavior at the HFs of the CM current, additional high-ac-voltage polypropylene foil capacitors are connected between the phase-terminal connection and the protective earth of the drive (Figure 4).

Base Configuration, with CM Chokes

Five commercially available feedthrough CM chokes, M1–M5, of three different types are used for the investigation (Table 1; for more tabulated data, we refer to [26]); both in the form of selected individual chokes and of several combinations of the individual chokes.

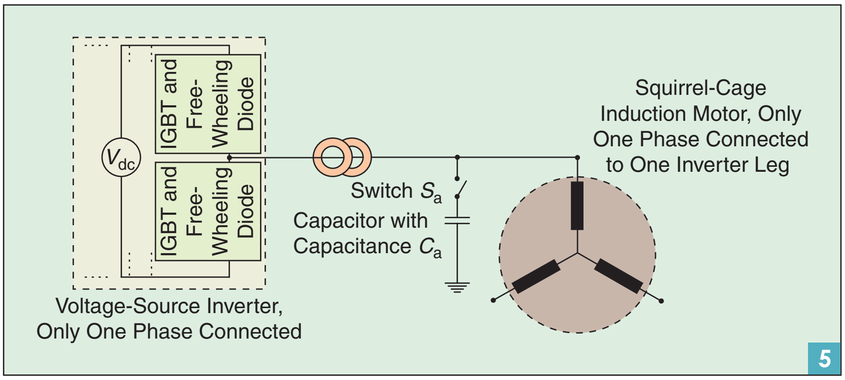


Base configuration: one motor terminal connected to one inverter leg and additional capacitors with capacitance C_a connected at the motor terminal.

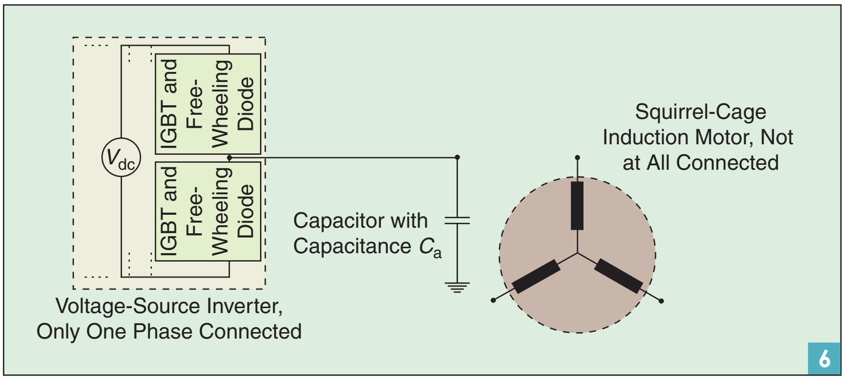
TABLE 1. PARAMETERS OF CM CHOKES USED.

Choke Label	Tabulated Inductance* (µH)	Window Diameter (mm)	Outer Diameter (mm)	Length (mm)
M1, M2	24.1 . . . 48.2	80	63	30
M3	23.3 . . . 46.6	63	50	30
M4, M5	13.2 . . . 29.7	63	50	20

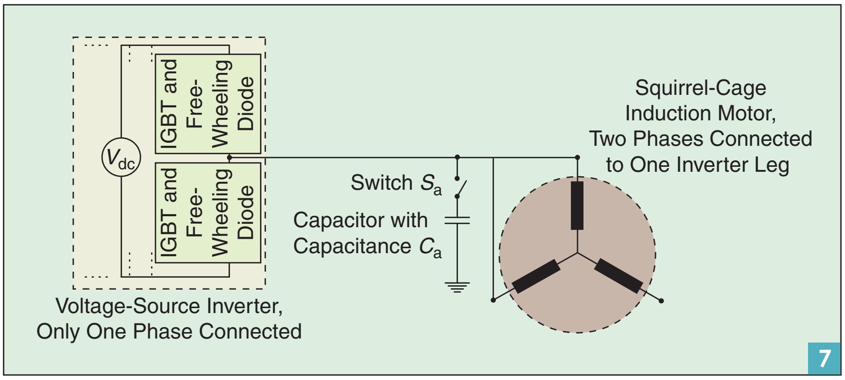
*A_L value at 10 kHz.



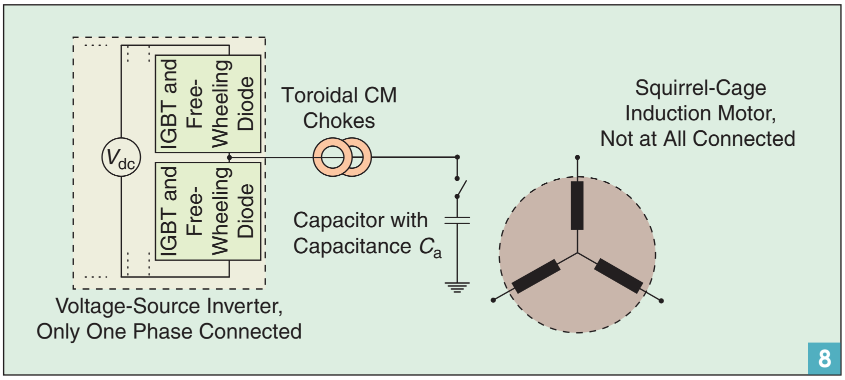
The base configuration with additional CM chokes. Compare with Figure 4.



Further configurations: none of the motor terminals, but additional capacitors with capacitance C_a connected to one inverter leg. Compare with Figure 4.



Further configurations: two of the motor terminals connected to one inverter leg and additional capacitors, with capacitance C_a connected at the motor terminal. Compare with Figure 4.



Configuration with additional CM chokes and none of the motor terminals connected. Compare with Figure 6.

For evaluation, the chokes are placed between the inverter and the motor. If connected, the additional capacitors are on the motor side of the choke (Figure 5). The tests are carried out with the different chokes and selected combinations, for different values of C_a.

Some Nomenclature

The measured currents and voltages are labeled according to the capacitance of the additional capacitors C_a and the label(s) of the installed choke(s). $I_{XnF,MY}$ and $V_{XnF,MY}$ are the current and voltage, with $C_a = XnF$ and choke(s) MY, respectively.

Other Configurations

In a subsequent step, the test setup is modified to further analyze the influence of the motor winding on the HF ground current: if the motor behaves mainly capacitively, as the simplified model suggests (see the "Background and Context" section), replacing the capacitively behaving motor terminal connection fully by an external capacitance instead of only increasing its capacitance would lead to very similar results. However, if the motor is not connected at all, the system is more likely to be underdamped, since the relative contribution of the stator housing toward the total resistance along the path of the HF ground current is understood to be much larger than the one of the additionally connected capacitors. To this aim, the inverter leg is either not connected to the motor at all but only with the capacitors (Figure 6) or to two of the three motor terminals (Figure 7). Because of the results obtained with these two configurations (see the "Results" section), the third option—all three motor terminals connected to one inverter leg was not investigated.

For all the three configurations, the use of CM chokes was investigated (Figure 8). The results obtained with the base configuration (see below) were used to select only two values of the additional capacitors, $C_a = 2.2$ nF and $C_a = 30$ nF.

Results

Base Configuration, Without CM Chokes

The peak current amplitude with neither additional capacitors nor CM chokes, $I_{p,0nF,0}$, is used as a reference value to quantify the influence of the additional capacitors C_a. With increasing value of C_a, the peak current amplitude increases (Table 2), reaching $I_{p,30nF,0} = 63.1\ A = 5.3 \times I_{p,0nF,0}$ at $C_a = 30$ nF (Figure 9).

As the peak amplitude of the HF ground current is approximately proportional to C, we write $I_p \propto C$. Then,

$$\frac{I_{p,C_a}}{I_{p,0nF}} \approx \frac{C_m + C_a}{C_m} = 1 + \frac{C_a}{C_m}, \quad (1)$$

where C_m is the contribution from the motor winding and is a function of the frequency.

We plot $I_{p,C_a}/I_{p,0nF}$ as a function of C_a (Figure 10), approximate $I_{p,C_a}/I_{p,0nF}$ with a second-order polynomial, and obtain

$$I_{p,C_a}/I_{p,0nF} = -0.0032\,C_a^2 + 0.234\,C_a + 1.1045. \quad (2)$$

Comparing the coefficient of the square term with those of the linear term and the constant in (2), we neglect the first. We compare (2) and (1) and further simplify $1.1 \approx 1$ to approximate the value of C_m,

$$C_m \approx \frac{1}{0.234}\ \text{nF} \approx 4.27\ \text{nF}, \quad (3)$$

which is a typical value for machines of this frame size. Note also that the polynomial (2) used to compute the effective value of C_m is based on an approximation over the different measurements with different additional values C_a and is thus an average over the frequency range occurring within these measurements. Furthermore, the values of C_m, notably, the value for $C_a = 0$ nF, will be somewhat smaller as the dv/dt is higher and results in a smaller penetration depth of the incoming wave into the stator winding. Such influence can be analyzed using complicated models, which are beyond and somewhat even in contrast to the aim of this article, as explained in the introduction.

Without additional capacitors, the dv/dt is approximately 2 kV/µs, and with $C_a = 30$ nF, it is approximately 1 kV/µs.

FIVE COMMERCIALLY AVAILABLE FEEDTHROUGH CM CHOKES OF THREE DIFFERENT TYPES ARE USED FOR THE INVESTIGATION.

TABLE 2. MEASURED AMPLITUDES OF HF GROUND CURRENT AND BASE CONFIGURATION, WITH NO CM CHOKES.

C_a (nF)	I_p (A)	$I_p/I_{p,0nF}$
0	11.9	1
2.2	20.7	1.8
10	36.8	3.1
20	53.8	4.5
30	63.1	5.3

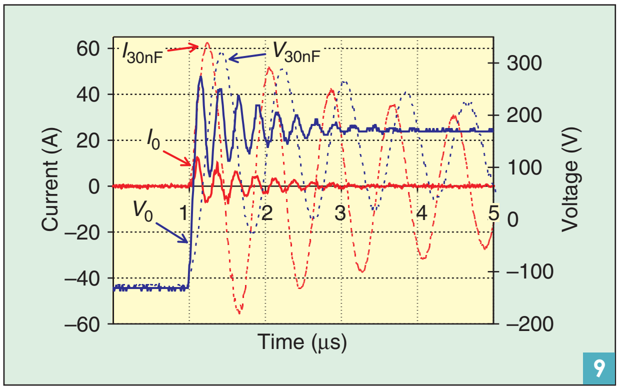
For $C_a = 30$ nF, the ring frequency is approximately 1 MHz, giving

$$L \approx \frac{10^9}{30 + 4.27} \frac{1}{(2\pi 10^6)^2}\,\text{H} = 0.739\ \mu\text{H}, \quad (4)$$

which is also a realistic value for the self-inductance L_{self} of the short motor leads, where we neglect the contribution of the motor winding because of the capacitive behavior of the motor. Drawing from the measurements without additional capacitance, we obtain $L_{self} = 10^9/4.27 \times 1/(2\pi\,4 \times 10^6)^2\text{H} = 0.37\ \mu\text{H}$, which is still in line with the previous figure, as $C_m = 4.27$ nF will have been taken somewhat too small and L also decreases with frequency.

Base Configuration, with CM Chokes

Measurements were taken for the different values of C_a (including $C_a = 0$ nF) with chokes 1) M3, 2) M1, 3) M1 and



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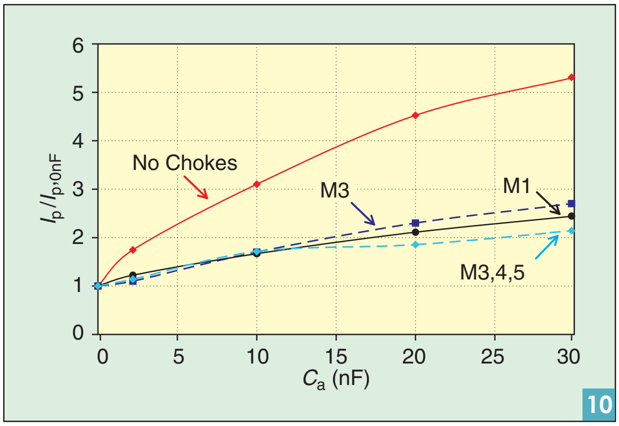
Base configuration: measured currents and voltages with $C_a = 0$ nF (I_0, V_0) and $C_a = 30$ nF (I_{30nF}, V_{30nF}).



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Base configuration: current increase with additional capacitance C_a without choke and with different chokes, $I_{p,0nF}$: peak amplitude with no additional capacitors, I_p : peak current amplitude with additional capacitors with capacitance C_a.

M2 together, and 4) M3, M4, and M5 together (Table 1). The results are summarized in Table 3.

First, the influence of the additional capacitors on the value of the peak current amplitude for different chokes is considered (Figure 10). For the given orders of magnitudes, the approximately linear increase of the peak ground current amplitude with increasing values of C_a is also found with the use of chokes.

With respect to the effectiveness of the chokes to reduce the ground current, chokes M1 and M3 with approximately the same tabulated inductances (M1: 24.1 . . . 48.2 µH, M3: 23.3 . . . 46.6 µH) also translate into approximately the same reduction of the HF ground current amplitude. This current reduction is approximately the same for all values of C_a, except for $C_a = 0$ nF: for $C_a = 2.2$ nF, the peak amplitude of the HF ground current is reduced down to 21 . . . 33%, depending on the type(s) and number of CM choke(s) used, for $C_a = 30$ nF, it is reduced down to 15 . . . 27%, for $C_a = 0$ nF; however, the current is only reduced down to 27 . . . 53% (Table 3). This finding is in line with the theoretical observation and earlier finding that peak currents resulting from higher capacitance values experience a greater percentage reduction than those resulting from the lower capacitance values (see Figure 3). The approximately 2 or 2.5 times higher inductances of the combinations of chokes—use of 3) M1 and M2 or 4) M3, M4, and M5 together, instead 1) M3 or 2) M1 alone do lead to an additional current reduction of approximately 10% (Table 3), since one choke alone already leads to a point of operation where a reasonable current reduction is obtained, what is again in line with the previous findings.

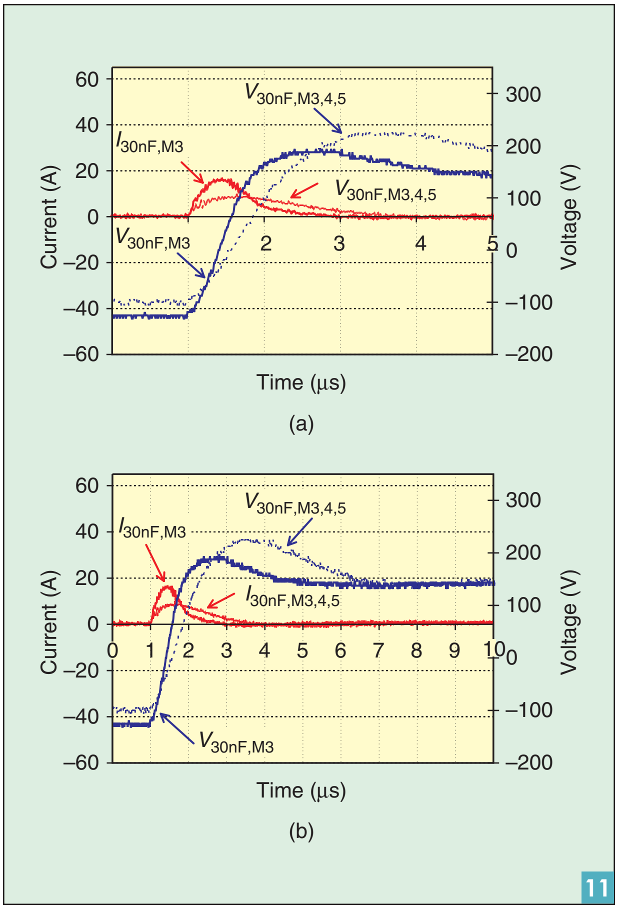
> THE TESTS ARE CARRIED OUT WITH THE DIFFERENT CHOKES AND SELECTED COMBINATIONS, FOR DIFFERENT VALUES OF C_a.

The comparatively large value of the choke inductance significantly reduces the ringing of the ground current, as can be clearly seen in the measurements. Exemplarily,

TABLE 3. MEASURED AMPLITUDES OF HF GROUND CURRENT, AND BASE CONFIGURATION WITH CM CHOKES.

C_a	Choke(s)	I_p (A)	$I_p/I_{p,0}$
No	M3	6.2	0.53
	M1	5.6	0.47
	M1, M2	3.1	0.26
	M3, M4, M5	4.4	0.37
2.2 nF	M3	6.9	0.33
	M1	6.9	0.33
	M1, M2	4.4	0.21
	M3, M4, M5	5.0	0.24
10 nF	M3	10.6	0.29
	M1	9.4	0.25
	M1, M2	6.3	0.17
	M3, M4, M5	7.5	0.20
20 nF	M3	14.4	0.27
	M1	11.9	0.22
	M1, M2	7.5	0.14
	M3, M4, M5	8.1	0.15
30 nF	M3	16.9	0.27
	M1	13.8	0.22
	M1, M2	6.9	0.11
	M3, M4, M5	9.4	0.15

$I_{p,0}$: peak current amplitude without chokes.



Base configuration: measured currents and voltages with $C_a = 30$ nF and choke M3 ($I_{30nF,M3}$, $V_{30nF,M3}$) and with $C_a = 30$ nF and chokes M3, M4, and M5 ($I_{30nF,M3,4,5}$, $V_{30nF,M3,4,5}$). Compare with Figure 9. (a) Zoom into the initial voltage and current rises. (b) Larger timescale than Figure 11(a).

Figure 11 shows the currents and voltages measured in the base configuration with $C_a = 30$ nF and choke M3, and with chokes M3, M4, and M5, using the same timescale as shown in Figure 9. As a matter of fact, for $C_a = 30$ nF, an increase of the period time by a factor of ten gives an inductance value of 73.9 μH. This corresponds well to the calculated total inductance of $\{M3 + M4 + M5 + L_{self}\} = \{(23.3\ldots46.6) + 2\times(13.2\ldots29.7) + (0.37\ldots0.739)\}\ \mu\text{H} = (50.07\ldots106.74)\ \mu\text{H} = 78.41\ \mu\text{H}_{av}$. In Figure 11, (b) shows the same results as in (a) but using a larger timescale. Because of the large damping of the system, and only approximately, oscillation occurs only for half of the period time.

CM CHOKES CAN BE A COST-EFFECTIVE METHOD FOR REDUCING GROUND CURRENTS.

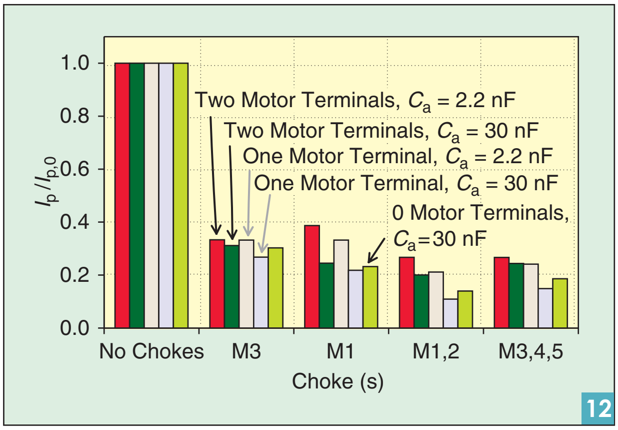
Other Configurations

In a subsequent step, the test setup is modified with respect to the number of motor terminals that are connected. The results of these investigations are summarized in Table 4 and also illustrated in Figure 12.

The results confirm that the influence of the motor winding on the HF ground current and its reduction achieved with the chokes is very small for sufficiently large additional values of the additional capacitor(s) C_a: the current reduction achieved with the chokes is almost independent of the number of connected motor terminals, except for the case of the motor not connected and $C_a = 2.2$ nF. For $C_a = 2.2$ nF, the system is underdamped, and a larger value of C_a is required to properly investigate the performances of the chokes under larger currents. As these larger values of C_a are already required to generate the large CM-current amplitudes that are typical with drives with comparatively large rated power—which are in the focus of this work—this effect needs to be paid attention to, notably when investigating drive systems with relatively small rated power but does not compromise the suitability of the low-cost, test bed presented.

Conclusions

When designing CM chokes for use in the inverter-output of higher-power inverter-based drive systems, the experimental evaluation of such chokes during the design stage is a



Current reduction with use of different chokes (different configurations number of connected motor terminals), C_a = 2.2 nF/30 nF; $I_{p,0}$: peak amplitude without chokes, I_p : peak current amplitude with chokes.

TABLE 4. MEASURED AMPLITUDES OF HF GROUND CURRENT WITH DIFFERENT CONFIGURATIONS.

	Number of Connected Motor Terminals					
	2		1		0	
C_a, Choke(s)	I_p (A)	$I_p/I_{p,0}$	I_p (A)	$I_p/I_{p,0}$	I_p (A)	$I_p/I_{p,0}$
2.2 nF						
M3	7.8	0.33	6.9	0.33	6.9	1.83*
M1	9.1	0.39	6.9	0.33	5.9	1.58*
M1, M2	6.3	0.27	4.4	0.21	4.1	1.08*
M3, M4, M5	6.3	0.27	5.0	0.24	5.62	1.50*
30 nF						
M3	21.9	0.31	16.9	0.27	20.3	0.30
M1	17.2	0.24	13.8	0.22	15.6	0.23
M1, M2	14.1	0.20	6.9	0.11	9.4	0.14
M3, M4, M5	17.1	0.24	9.4	0.15	12.5	0.19

$I_{p,0}$: peak current without chokes.

*System is underdamped. A higher value of C_a is required.

valuable tool. For this purpose, a low-cost technique using a low-power test bed can be applied to replace a more costly, higher-power test bed. This was illustrated exemplarily by using a 4-kW drive to experimentally investigate the performance of several CM chokes to reduce HF ground currents with amplitudes typical for drives up to 500-kW rated power. The results obtained with this test bed were analyzed theoretically in a simple, straightforward manner, which can be used for the development of similar test beds of this kind in other contexts.

THE COMPARATIVELY LARGE VALUE OF THE CHOKE INDUCTANCE SIGNIFICANTLY REDUCES THE RINGING OF THE GROUND CURRENT.

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